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EXPERIENCES WITH A SIMPLE
SKIN FRICTION BALANCE DESIGN

BY
E. L. WHITE
AEROMECHANICS DIVISION
FLIGHT DYNAMICS LABORATORY
WRIGHT-PATTERSON AFB, OHIO

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AERONAUTICAL LABORATORIES
FLIGHT DYNAMICS LABORATORY
AEROMECHANICS DIVISION
EXPERIMENTAL ENGINEERING BRANCH
WRIGHT-PATTERSON AFB, OHIO 45433

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1. INTRODUCTION

The Flight Dynamics Laboratory is engaged in compressible boundary layer research in our M=3 and M=6 High Reynolds Number Facilities (HRNF). A good direct reading skin friction balance is required to accurately define the shearing stresses on smooth and rough surfaces and for development of indirect measurement techniques. Initially, Kistler direct reading skin friction balances were used but there were problems with damping and repairing our balances and Kistler no longer produces them. They were also too large for most models which are tested in these facilities. Figures 1 and 2 show the test section geometries and the nominal test conditions for these two test facilities. Basically the balance size is suitable only for tunnel wall or flat plate model installations. Therefore when a small balance design was brought to our attention by Virginia Research Associates, several were purchased for evaluation.

2. SKIN FRICTION BALANCE DESCRIPTION

The Virginia Research Associates (VRA) skin friction balance design (Fig 3) is based on the Kistler-Morse Deflection Sensor Cartridge (DSC). It consists of a cantilever beam with two silicon crystals glass-fused to the beam. The two crystals are wired as the active elements of a wheatstone bridge. The claimed performance of the DSC shows excellent linearity, repeatability, thermal stability, and hysteresis characteristics (\leq metal foil strain gage). Thermal sensitivity variation is about three times greater (.01 percent of full scale/degree F) than for a metal foil strain gage. The maximum rated full scale deflection of the end of the DSC beam is $\pm .015$ IN. The original version of the VRA design

which was 1.75 IN long overall had an effective beam length .25 IN longer than the basic DSC (1.50 IN). With a nominal maximum shearing force of 5 grams (.24 psi shearing stress) on the sensing element, the deflection of the sensing element is less than .0005 IN. The deflection for the same load on the 2.75 IN long design is .002 IN.

The balance (Fig 3) consists of a water cooled housing which provides for a press fit with the base of the DSC. The sensing element is press fit on the other end of the DSC and made flush with the top of the housing. The gap between the sensing element and housing is .005 inch.

3. M=6 HRNF Tests

The first tests with a VRA balance were performed in the M=6 High Reynolds Number Facility (HRNF) which operates at a stagnation temperature of 1100 degrees R. The overall length of this balance was 1.75 IN. It was mounted about 17 inches aft of the leading edge of a flat plate. A model support system injected the model into the flow after supersonic flow was established. There was no provision for mechanical vibration damping of the balance. The calibration factor was furnished with the balance. The test data was primarily recorded by Hewlett-Packard X-Y recorders. A slow speed digital recording system was also used. The first series of runs showed that vibration damping was required. A zero shift occurred in the output signal when the test cabin pressure dropped after establishing flow and before the flat plate was inserted into the flow. The output was also too low to obtain any reasonable resolution or accuracy. Bench tests were performed and it was found that the zero shift was due to the drop in test cabin pressure.

At this point it was decided to try an extended length version of the balance design in an attempt to get the output to a more acceptable level. The effective length of the beam was doubled by extending the length of the sensing element and balance housing. The extended length design is shown in Figure 3. To simplify the installation and testing, the M=3 HRNF was used for this test. The thermal environment is also less severe since the total temperature goes from ambient to -40 degrees F.

4. M=3 HRNF Test

The balance was calibrated with gravity loading and a linear and repeatable plot was obtained (Fig 4). The balance housing was then filled with 30,000 centistoke silicone oil and pressure and temperature effects evaluated. Before consistent pressure effect data could be obtained the silicone oil had to be thoroughly outgassed. The balance output varied as the gas bubbles worked their way through the fluid. The pressure was maintained below the lowest expected wall static pressure until there was no more variation in the balance output. Pressure effects on this damped balance were much less than for the original balance. The shift in the output of the extended length balance when the pressure is reduced to the lowest expected wall pressure (2 psia), is one percent of the full scale shearing stress of 0.1 psi (max shearing stress measured in M=3 HRNF). Since the first tests with this balance were planned for the M=3 facility, below ambient temperature effects were checked. Gaseous CO₂ was directed at the exposed surface of the balance to simulate the decreasing wall temperature in the M=3 facility. A thermocouple inside the balance housing monitored the temperature. The temperature effect due to cooling with CO₂ on the surface was about 0.5 percent/degree F based on a full scale shearing stress of 0.1 psi.

The balance was installed in the bottom wall of the tunnel as shown in Fig 2. Test runs were made at a series of total pressures (P_0) and at the various pressure levels, incremental changes of ± 20 psi were made to check the resolution capability of the balance. Normal run times were between 2 and 3 minutes in duration. In addition to the mechanical vibration damping provided by the silicone oil, the recorded signal was improved by using electronic filtering particularly at the higher stagnation pressures. At $P_0 = 560$ psia with the bandwidth reduced to 10 Hz, the noise was 3.5 percent peak-to-peak of the DC signal. The balance output signal followed the stagnation pressure very well (Fig 5).

Below a stagnation pressure of 200 psia, a problem developed which made the balance data practically useless. A random variation of the output signal was observed which did not correlate with the stagnation pressure (Fig 6). To check for a possible flow problem at these pressures and at this particular tunnel station, a Kulite high frequency response surface mounted pressure transducer was mounted at the side of the balance and schlieren was set up to observe the flow at the wall. There was no correlation of the Kulite output with the balance output and the schlieren showed nothing unusual. The only thing unusual was oil streaks on the downstream side of the balance gap. The behavior of the data and the oil streaks suggest that droplets of oil are being pumped out of the balance through the gap. As a droplet works its way through the gap, a negative load is applied to the sensing element which results in the data signal shifting negative and when the droplet exits the gap, the signal goes positive. Other droplets are following and the cycle repeats.

An attempt was made to flush the silicone oil out of the balance with xylene to determine the response of the balance without oil. At first the test data did not show any erratic behavior but the effect soon returned at stagnation pressures below 200 psia. It is doubtful that all of the oil was flushed out of the balance.

The balance was then refilled with 100,000 centistoke silicone oil to determine if the more viscous oil would solve the problem. This oil improved the damping of the balance but the zero returns were not as good and the erratic behavior of the data was still present below $P_0 = 200$ psia.

A second balance which never had any oil in it was installed in the wind tunnel. From this dry (no oil) balance the data demonstrated that mechanical vibration damping is required above $P_0 = 300$ psia. Two runs were made at stagnation pressures below 200 psia and there was no evidence of any erratic data. Each run was about 2-3/4 minutes in duration.

Time did not permit calibration or bench tests before this balance was installed in the test facility. This led to misorientation of the balance in the wind tunnel. Bench tests and calibrations were performed after the wind tunnel tests and revealed that the most sensitive axis of the balance was 60 degrees off the tunnel centerline.

Numerous runs of representative data are plotted on Figure 7. The data is compared with a curve derived by A. W. Fiore which is based on measurements by Fiore and others at a nominal Mach number of 3 and a near adiabatic wall with zero pressure gradient (Reference 1). Above $P_0 = 200$ psia, the data recorded when the balance was filled with 100,000 centistoke silicone oil follows the line very well. However only one run was made in this pressure range and it is noted that two other runs with 30,000 centistoke oil also follow the line well.

Below $P_0 = 200$ psia the data from the oil damped balance is questionable since it was very erratic at times (Reference Figure 6) and even though the data was reasonably steady at times, it is suspect.

Since the misalignment of the dry balance (no oil) was not discovered until after the test, there is insufficient data to explain the different slope. The data represents two runs and is linear. The most important feature of this data is the lack of any evidence of erratic balance output.

5. CONCLUSIONS

Based on the test data available, the following conclusions can be made for using the VRA balance in the M=3 HRNF.

1. Mechanical vibration damping is required above $P_0 = 300$ psia.
2. 100K centistoke silicone oil provided sufficient damping to eliminate the need for electronic filtering in the frequency response range of the X-Y recorder.
3. A second dry (no oil) balance must be used below $P_0 = 200$ psia (wall static pressure ≤ 6 psia).
4. With some temperature control (circulating tap water), the balance temperature change can be held to a maximum of 3 degree F for a three minute test. In terms of shearing stress this would be equivalent to about 1.5 percent of full scale ($\approx .1$ psi).
5. The output shift due to a pressure change from atmospheric to the minimum wall pressure (2 psia) was equivalent to .001 psi or 1 percent of full scale ($\approx .1$ psi).
6. The VRA design responds to a shearing force from almost any azimuth angle except near ± 90 degrees from its most sensitive axis.

7. The balances will respond to changes in skin friction due to 20 psi change in P_0 .

8. The overall length of the balance (2.75 IN) restricts its use to measurements on the tunnel walls in the $M=3$ HRNF and to flat plate measurements in the $M=6$ HRNF if a special fairing is installed on the bottom of the plate.

Despite the fact that the DSC in the VRA skin friction balance is operating at less than 1.5 percent of the rated full scale output of the unit, it performed very well in bench tests. However there are certain aerodynamic effects to consider in any skin friction balance design for optimum accuracy of the data.

Jerry Allen of NASA-Langley conducted an extensive study of potential error sources in skin friction balance measurements in supersonic flow (Reference 2). He found that the total force acting on a sensing element is a combination of the skin friction, lip force and normal force. His results show that the optimum design is a null positioned parallel linkage balance with a sharp edged sensing element and a closely controlled gap size. A single pivot or cantilevered beam configuration such as the VRA design can respond to normal and lip forces since these are essentially moment sensing devices (Fig 8). Position nulling of the sensing element maintains a constant gap configuration and eliminates another potential source of error. The VRA design has a cantilevered beam which is not null positioned and the gap which exists when the sensing element is not loaded, may be too large. The gap to sensing element diameter ratio is .021 which is twice the maximum ratio investigated by Allen. Even though his data shows improvement in balance performance as a ratio of .010 is approached, it appears to us there would be a point where this trend would be reversed. A sharp lip was put on the second VRA balance but the first has a lip to sensing element diameter ratio

of .0625 whereas the maximum ratio investigated by Allen was .05. The greater this ratio the greater the measurement error may be. Errors which are due to misalignment or lack of flushness of the sensing element with the model surface are minimized by following Allen's design improvements.

6. RECOMMENDATIONS FOR USE IN M=3 HRNF

1. Two separate balances are required, one filled with 100,000 centistoke oil and no oil in the other.

2. The edge of the sensing elements should be sharp and the ratio of the gap size to the sensing element diameter should be between .006 and .010.

3. Install a thermal insulator between the sensing element and the DSC. The cooling coils do not control the heat transfer through the sensing element. A fine wire thermocouple should be welded to the DSC just above the RTV potting.

4. The balance filled with oil should be thoroughly outgassed before a wind tunnel test.

5. Each balance should be bench tested for pressure and temperature effects.

6. Additional testing is required in the M=3 HRNF to resolve the data slope change experienced with the dry balance.

After following the above recommendations, there are two potential sources for errors which cannot be controlled with the VRA design. The first is the effect of normal force acting on the cantilevered beam and the second is the effect from a varying gap configuration due to the non-nulling design.

The search is continuing for a smaller balance design. At the present, a shortened version of the NASA-Langley design is being prepared for testing. The basic housing diameter is the same as the Kistler balance but the overall length, although shorter than the NASA design, is longer than the Kistler design. The NASA design incorporates all of the recommendations of Allen.

REFERENCE

1. Fiore, A. W., "Skin Friction Measurements at a Mach Number of Three and Momentum Thickness Reynolds Numbers up to a Half Million," AFFDL-TR-79-3136, Sep 1980.
2. Allen, J. M., "Improved Sensing Element for Skin-Friction Balance Measurements," AIAA Journal Vol 18, No 11, Nov 1980, pp 1342-1345.

M=6 HIGH REYNOLDS NUMBER FACILITY

P_o	T_o	RN/FT.
PSIA	$^{\circ}R$	—
700	1100	10×10^6
2100	1100	30×10^6

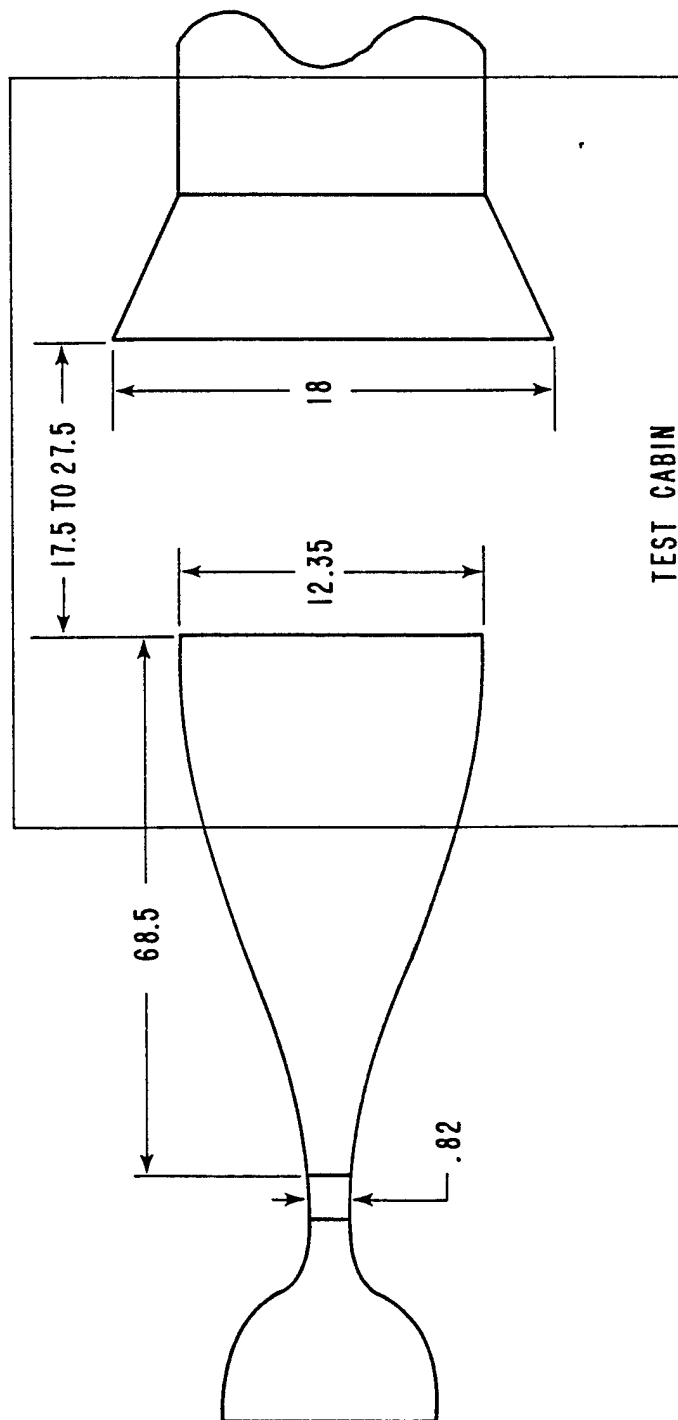
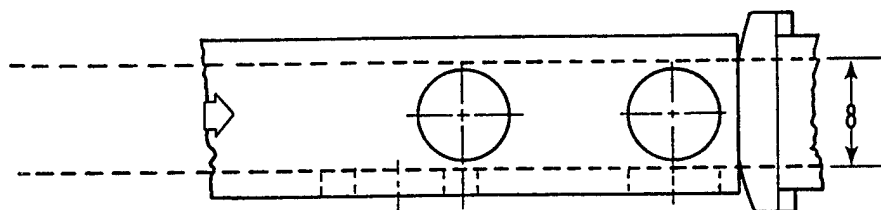


FIGURE 1

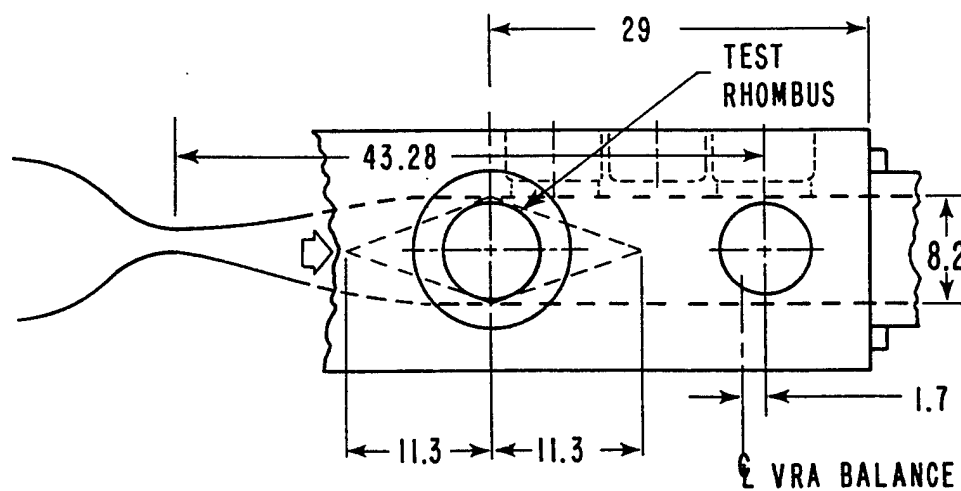
M = 3 HIGH REYNOLDS NUMBER FACILITY

P_o	RN / FT.
PSIA	—
50	10×10^6
600	100×10^6

NO T_o CONTROL



TUNNEL TOP VIEW



TUNNEL SIDE VIEW

FIGURE 2

VRA SKIN FRICTION BALANCE

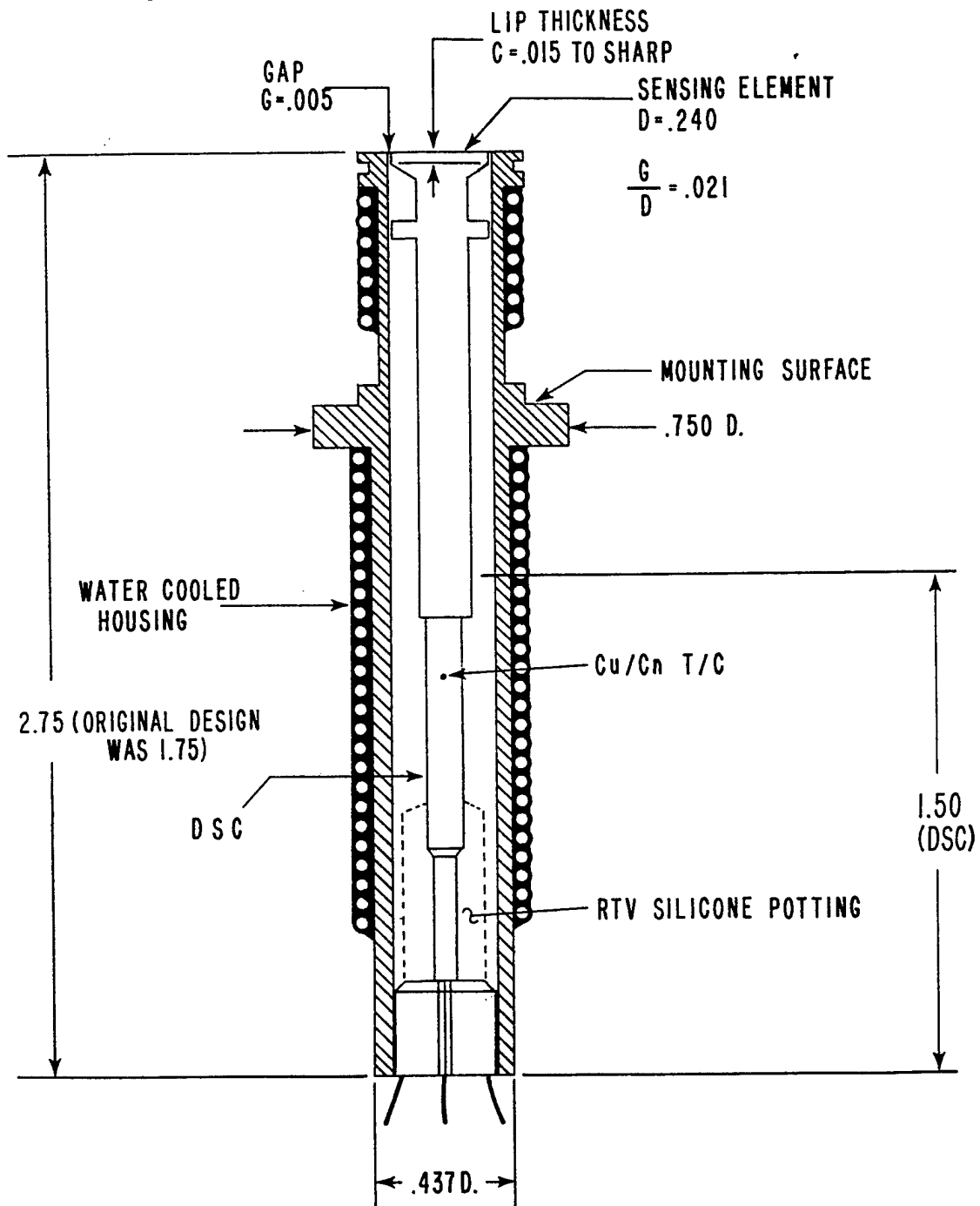


FIGURE 3

FORCE CALIBRATION OF VRA SKIN FRICTION BALANCE

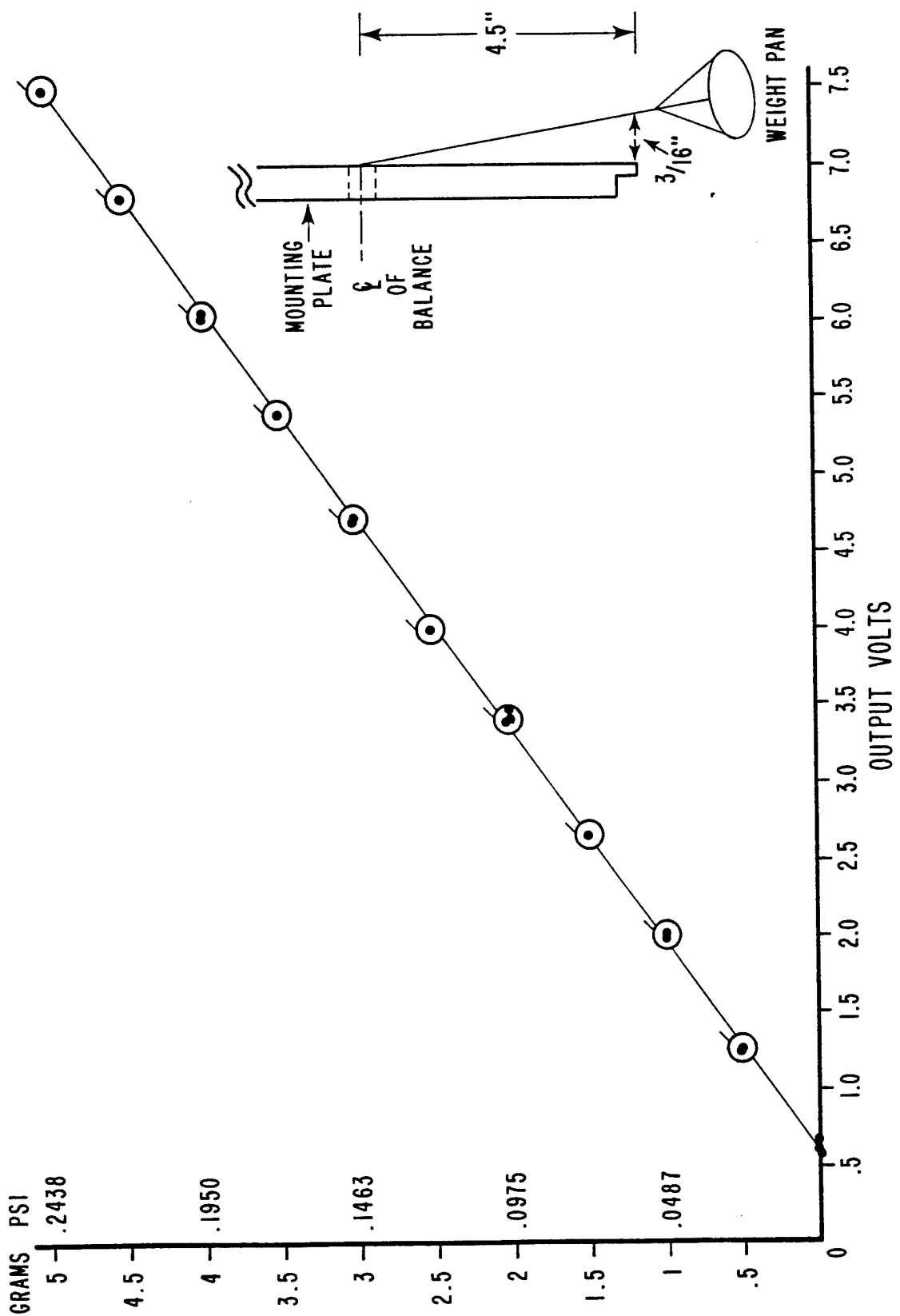
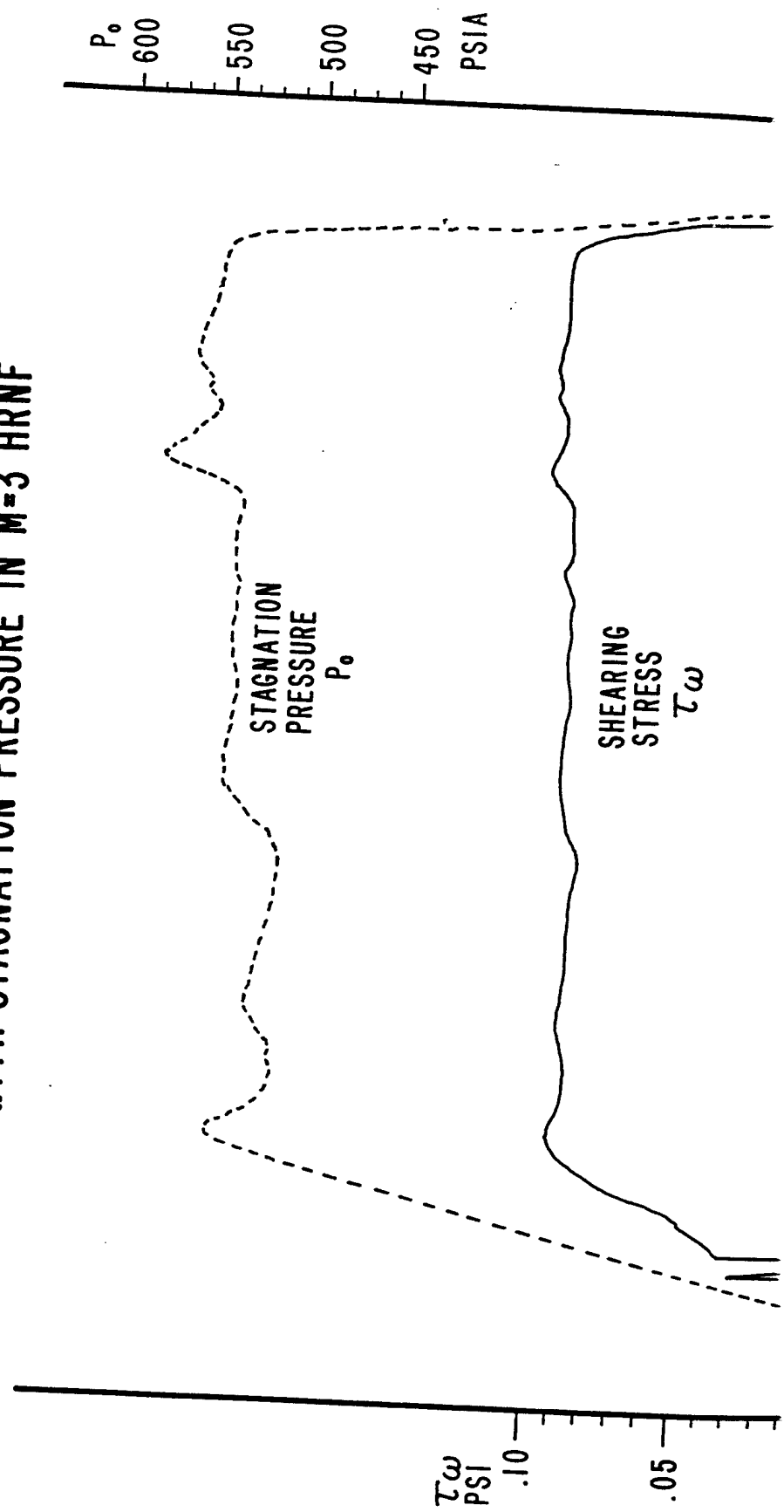


FIGURE 4

VARIATION OF MEASURED SHEARING STRESS WITH STAGNATION PRESSURE IN M=3 HRNF



RESPONSE OF VRA BALANCE WITH SILICONE OIL

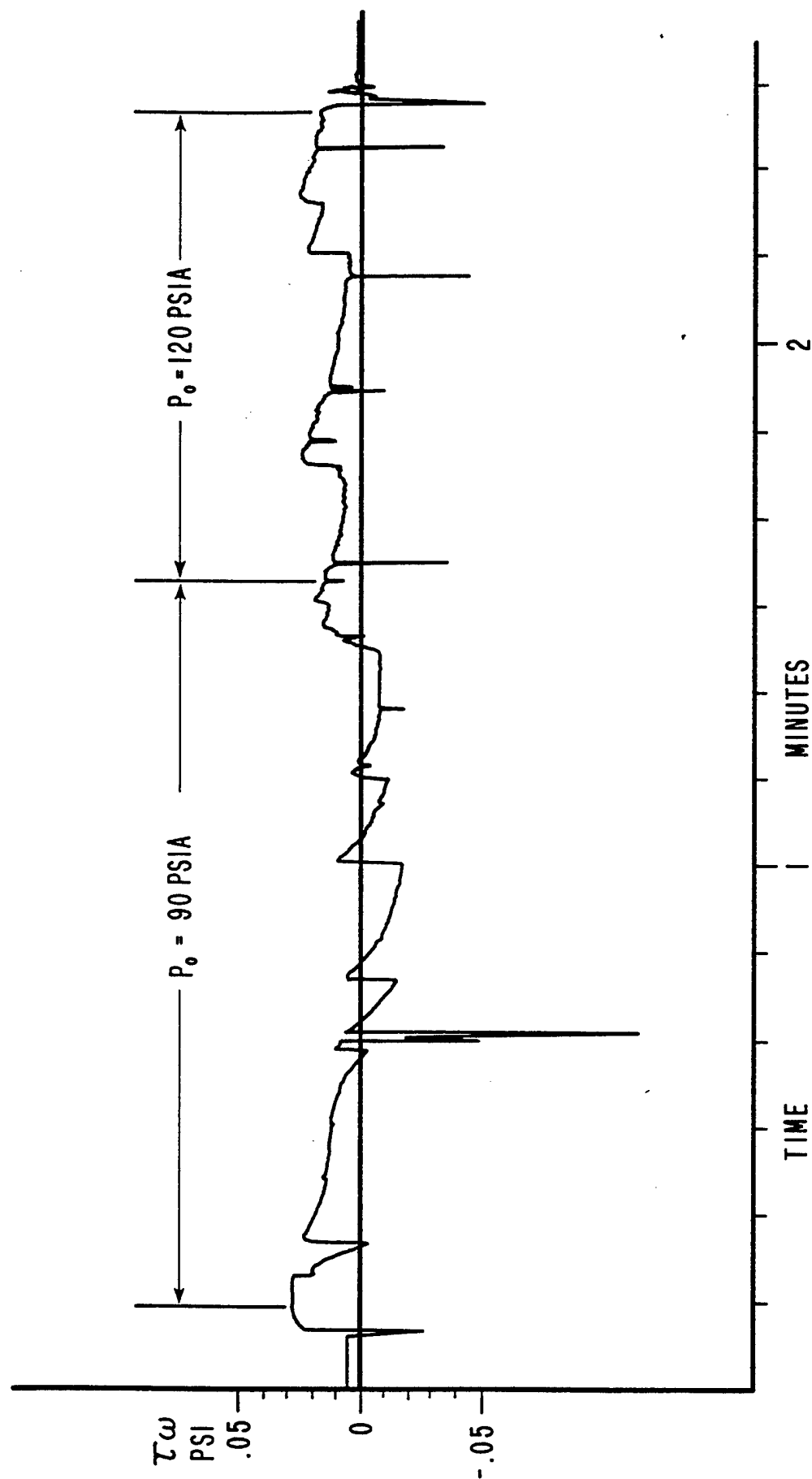


FIGURE 6

VRA SKIN FRICTION BALANCES NRS. 1 & 2 EVALUATION M = 3 HIGH REYNOLDS NUMBER FACILITY

- 30K CS OIL
- 100K CS OIL
- △ OIL FLUSHED
- ◇ NO OIL

FROM EMPIRICAL EXPRESSION BY A.W. FIORE (1)

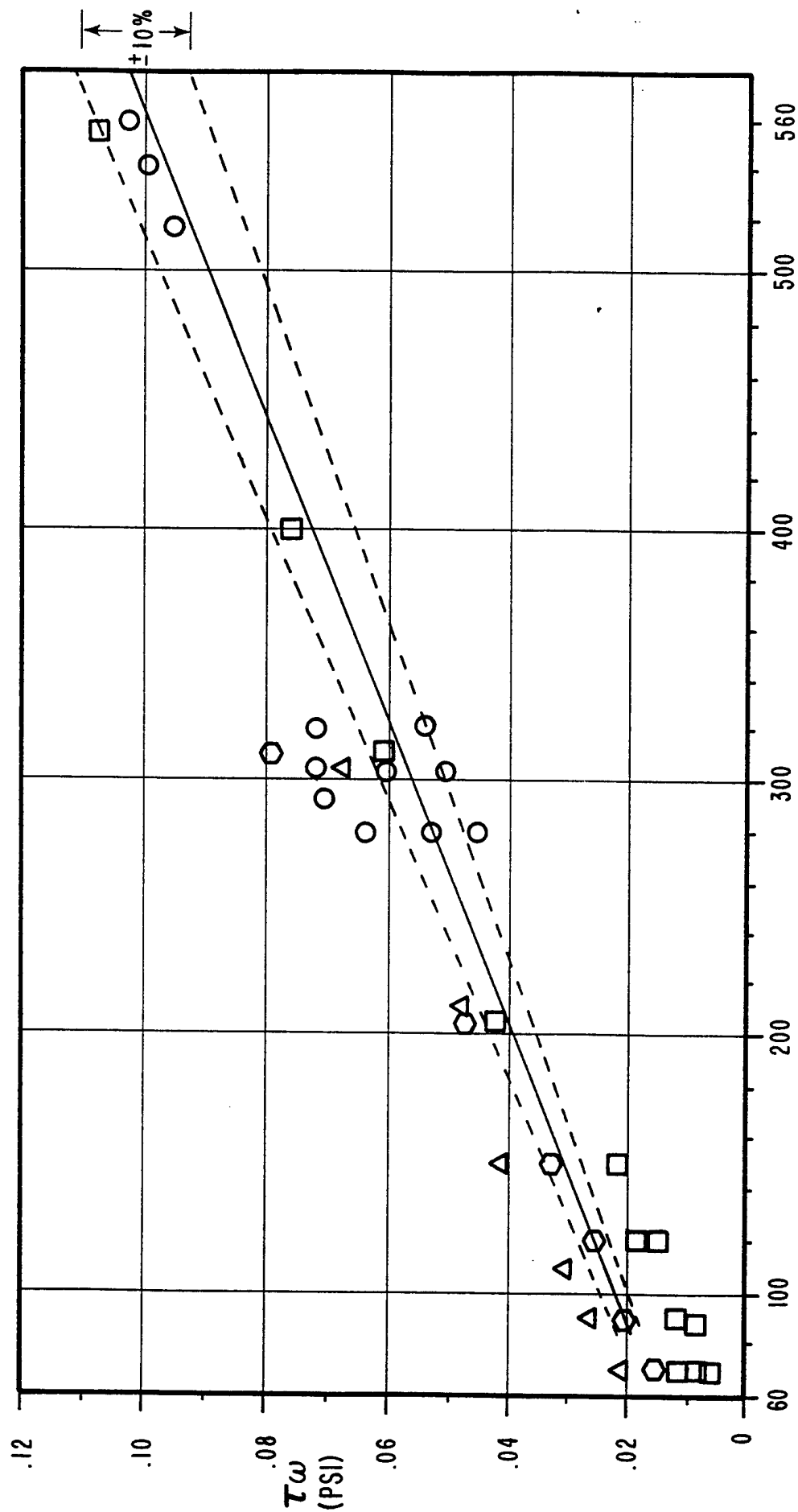
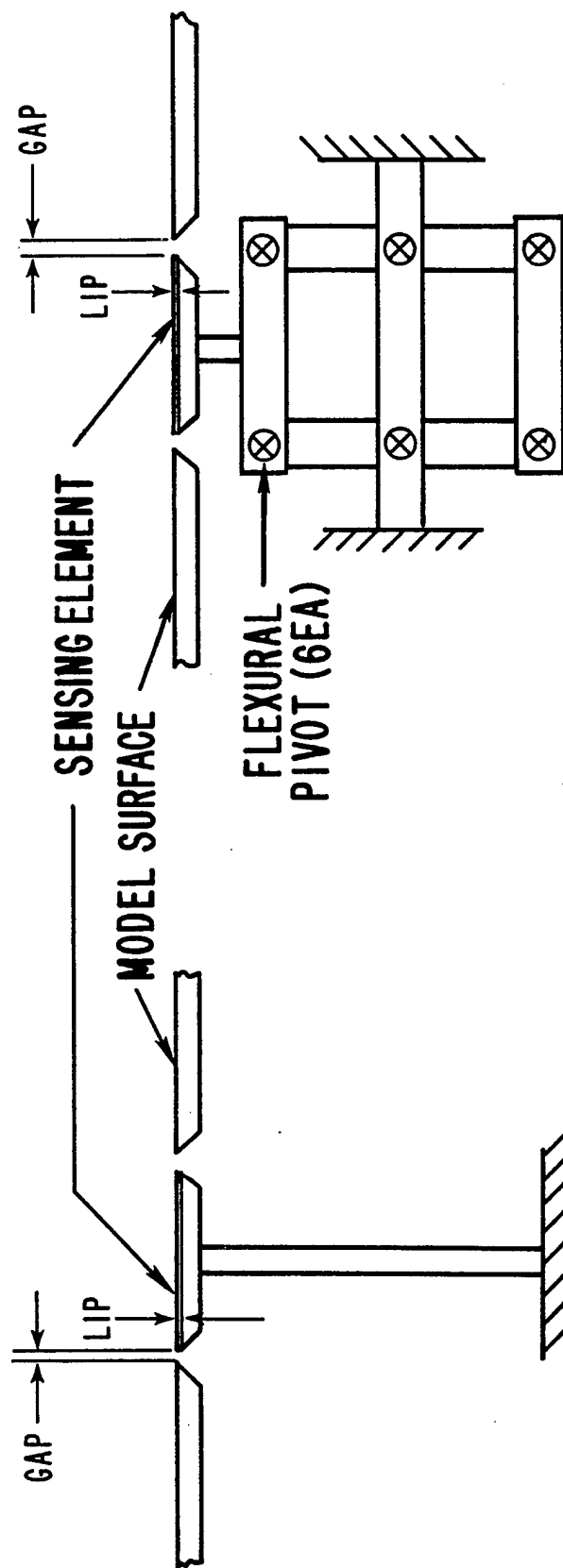


FIGURE 7

DIRECT MEASUREMENT SKIN FRICTION BALANCES

BASIC DESIGNS



CANTILEVERED OR PIVOTED BEAM
VRA

FLEXURAL
PIVOT (6EA)

OSCILLATING DOUBLE
4 BAR LINKAGE
NASA - LRC

FIGURE 8